

THERMOMAGNETIC ANALYSIS OF METEORITES, 4. UREILITES

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Abstract - Samples of all available ureilites have been analyzed thermo-magnetically. For three of the six (Dyalpur, Goalpara and Haverö) we find evidence for only low-nickel ( $\leq 2\%$ ) metallic-iron as the magnetic component and the  $J_s$ -T curves were reversible. In the Novo Urei ureilite, magnetite in addition to low-nickel metallic-iron was indicated and again the  $J_s$ -T curve was reversible. For the two badly weathered ureilites, Dingo Pup Donga and North Haig, indication was also found that both initial magnetite and low-nickel metallic-iron were present. However, the  $J_s$ -T curves were somewhat irreversible and the final saturation magnetization was 20% and 50% greater than initially for North Haig and Dingo Pup Donga, respectively. This behavior is interpreted to be the result of magnetite production from a secondary iron oxide during the experiment.

## 1. INTRODUCTION

In the first three papers of this series [1,2,3] we reported the saturation magnetization vs. temperature ( $J_s$ -T) analyses of all 38 of the carbonaceous chondrites. This paper presents the results of similar analyses of all six of the carbonaceous achondrites, the ureilites. Although seven ureilites are known, one has been lost and is therefore not available for study [4].

The achondrites in general are a chemically heterogeneous group of meteorites classed together on the basis of their lack of chondrules, the distinguishing feature of the chondrites. They are commonly more coarsely crystallized than are the chondrites and appear more similar to terrestrial rocks than do chondrites. In general achondrites are almost entirely lacking in nickel-iron, the ureilites representing an exception to the rule. Thus the ureilites form a unique group within the achondrites, being noteworthy by the presence of carbon, of diamonds and appreciable nickel-iron.

The ureilites resemble both the olivine-hyperthene chondrites (on the basis of their major elements) and the carbonaceous chondrites (on the basis of chemistry especially with regard to carbon as well as petrologically). Both Mueller [5] and Vdovykin [6] conclude that ureilites arise as the product of shock recrystallization of carbonaceous chondrite material. Wiik [7] argued that the ureilites were almost certainly not derived from any other meteorite classes by the classic mechanism of differentiation; and suggested that an alternative is that ureilites represent equilibrium condensation products from the original cosmic nuclide mix of elements.

At one time the presence of diamonds in the ureilites was taken to suggest that they must have originated deep within a parent body of lunar size or greater [8,9]. However, there appears to be little doubt that the ureilites have been heavily shocked [5,6,10,11] and the diamonds are now

generally regarded to be of shock origin [10]. According to Anders [12] and Wlotzka [13] there is little doubt that the carbonaceous material and probably also the metal found within the veins of ureilites represents foreign material introduced late in the history of the meteorite.

Whatever the detailed origin and history of the ureilites may be, the presence of several weight per cent of carbon suggests some relationship with the carbonaceous chondrites and so we now present thermomagnetic analyses of the ureilites following our similar analyses on the carbonaceous chondrites [1-3].

The experimental technique utilized in this study was described earlier [1,14] and will not be repeated here.

## 2. RESULTS AND DISCUSSION

In our studies of the thermomagnetic properties of the carbonaceous chondrites we found that the C1 chondrites were characterized by containing magnetite as the principal magnetic phase. Five of the 18 C2 and four of the 13 C3 chondrites were similarly characterized. A second major grouping with regard to magnetic characteristics of carbonaceous chondrites was occupied by over half of the C2 and C3 chondrites. These were characterized most prominently by the presence of a weakly magnetic substance (we think troilite) which altered during the course of the experiment into magnetite. It was found that the saturation magnetization was considerably larger at the end of the experiment than observed initially, due to magnetite production. Relatively few samples of the carbonaceous chondrites were found to contain metallic nickel-iron, e.g., none of the C1 chondrites, five of the C2 chondrites, five of the C3 chondrites and one of the two C4 chondrites.

However the most persistent feature of the  $J_s$ -T curve for the six ureilites is the presence of low-nickel ( $\leq 2\%$ ) metallic-iron. Fig. 1a-c sets forth the  $J_s$ -T curves for the Dyalpur, Goalpara and Haverö ureilites. There is little evidence for any magnetic species other than the low-nickel metallic-iron in these meteorites. There is a suggestion during the heating portion of the Goalpara sample for a minor magnetite component (the inflection point around 500-600°C), but it is absent during cooling. Basically, however, only low-nickel metallic-iron is indicated as a magnetic mineral.

The situation with respect to the thermomagnetic analysis of Novo Urei (Fig. 2) is only slightly more complicated. There we see indication of a substantial magnetite component accompanying the ever-present (in ureilites) low-nickel metallic-iron. There is no evidence in either Fig. 1 or Fig. 2 for magnetite production during the course of the experiment.

The remaining two ureilites, Dingo Pup Donga and North Haig, are both badly weathered samples as opposed to the other four which appear quite fresh and unweathered. The  $J_s$ -T curves of these two samples show indication of initial magnetite, low-nickel metallic-iron and additional production of magnetite during the course of the experiment. In our earlier work on the carbonaceous chondrites, we attributed similar behavior to oxidation of triolite to magnetite. However, Vdovykin [6] noted that both Dingo Pup Donga and North Haig contain secondary oxides of iron, e.g. goethite ( $\alpha\text{FeOOH}$ ) and limonite ( $\text{FeOOH}\cdot n\text{H}_2\text{O}$ ). Since the saturation magnetization of these oxides is considerably lower than that of magnetite, we would expect a rise in saturation magnetization if these secondary oxides are reduced to magnetite during the course of the experiment. Since we maintain the oxygen fugacity in the magnetite stability field, we would expect magnetite production from these other iron oxides. At any rate the magnetite production raises the saturation

magnetization by only about 20% and 50% in the North Haig and Dingo Pup Donga samples, respectively. This can be compared with the production in the C2 and C3 chondrites in which magnetite production raised the saturation magnetization by factors ranging from ~20% up to a factor of about 10, commonly being a factor of 2-4. For comparison, Fig. 4a and b shows the  $J_s$ -T curves for iron powder run first under vacuum ( $\sim 10^{-5}$  torr) then under stability conditions in our controlled atmosphere (in this case using only 8-1/2%  $H_2$  in  $N_2$ ). The behavior observed under vacuum conditions is obviously unsatisfactory if one is dealing with a sample containing iron, especially of small grain size such as found in ureilites and some C2 and C3 chondrites. However, it is seen in Fig. 4b that the behavior under the controlled gas system is much better. The slight decrease in the saturation moment on the heating cycle between 400° and 750°C is probably due to a minor amount of oxidation occurring even in this atmosphere. A stronger reducing atmosphere (21%  $H_2$  in  $N_2$ ) has now been utilized and virtually coincident heating and cooling paths were observed. The small amount of magnetite formed in Fig. 4b during heating appears to have been reduced back to iron upon cooling. The behavior in our atmosphere (especially with 21%  $H_2$  in  $N_2$ ) is far superior to vacuum conditions and is certainly adequate for most purposes. Furthermore, we have presented an extreme case, the finely divided powder presenting a very large surface for possible oxidation. Better behavior might be expected for meteorite materials run as whole pieces as is demonstrated by the data shown in Fig. 1a-c, where the only magnetic component indicated was metallic-iron of low nickel content and the curves are virtually coincident even when the 8-1/2%  $H_2$  in  $N_2$  atmosphere was used.

A major advantage of our controlled atmosphere, i.e., maintaining stability for samples containing both magnetite and iron, is demonstrated by the data depicted in Fig. 2, the  $J_s$ -T curve for the Novo Urei ureilite. It can be

seen from this figure that two magnetic components are present. Upon heating the saturation magnetization decreases rather abruptly at about 580°C as the temperature rises above the Curie point of magnetite. Above that temperature we observe a second component, metallic iron, which is indicated by the Curie temperature of 770°C. This component is almost pure iron ( $\leq 2\%$  Ni) as indicated by the Curie temperature and lack of  $\gamma \rightarrow \alpha$  transition. (See Fig. 5a in ref. [2] for an example of the  $\gamma \rightarrow \alpha$  transition which occurred in the Al Rais C2 chondrite). The most significant aspect of the  $J_s$ -T curve in Fig. 2 is demonstrated by the near coincidence of the heating and cooling curves. This near coincidence attests to our ability to heat meteorite samples (typically  $\leq 1$  mg) to temperatures of  $\sim 800^\circ\text{C}$  without significantly changing the oxidation state of the magnetite and metallic iron present. As noted previously, the saturation magnetization of iron is greater than that of magnetite. Thus, any change in the relative amount of iron and magnetite present in the Novo Urei sample (due to oxidation or reduction) would have caused the cooling curve to deviate significantly from the heating curve.

We have demonstrated here that, by maintaining the proper oxygen fugacity, it is possible to heat carbonaceous meteorites containing magnetite, metallic iron, or a combination of the two to temperatures as high as  $\sim 800^\circ\text{C}$  without significantly changing the oxidation state of those magnetic components. From our samples of Dyalpur, Goalpara, Haverö or Novo Urei, we expect that the Thellier technique could be readily applied for paleointensity estimates, providing that the proper oxygen fugacity was maintained during heating.

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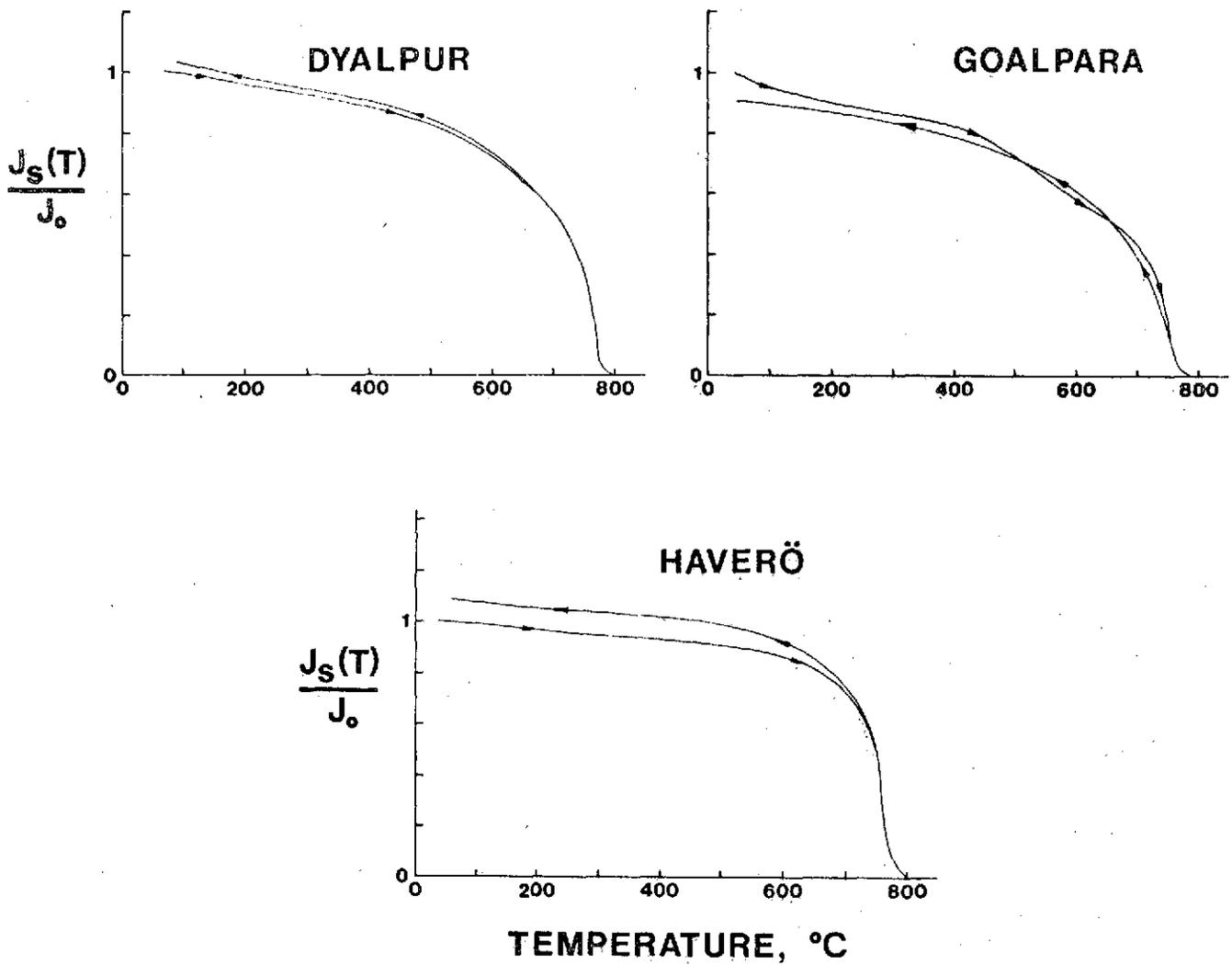


Fig. 1. Saturation magnetization vs. temperature ( $J_s$ -T) curves for the Dyalpur, Goalpara, and Haverö ureilites. These curves are indicative of the presence of low-nickel ( $\leq 2\%$ ) metallic-iron and no other magnetic component.

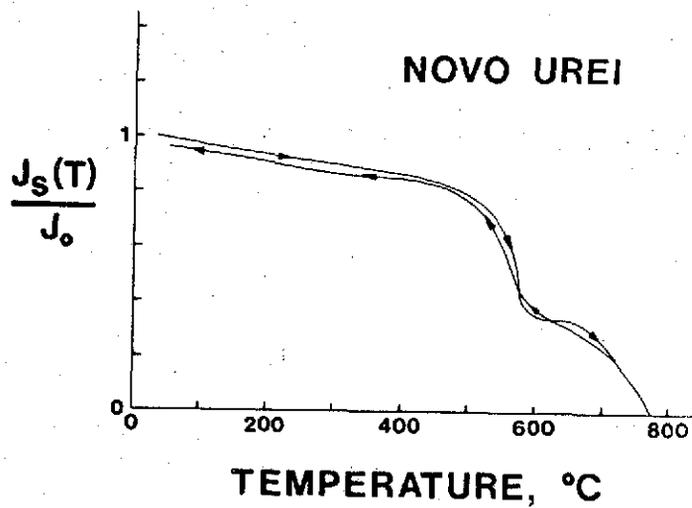


Fig. 2. Saturation magnetization vs. temperature ( $J_S$ -T) curve for the Novo-Urei ureilite. This curve indicates substantial contribution from both magnetite and low-nickel ( $< 2\%$ ) metallic-iron as the only magnetic minerals of any consequence in Novo-Urei.

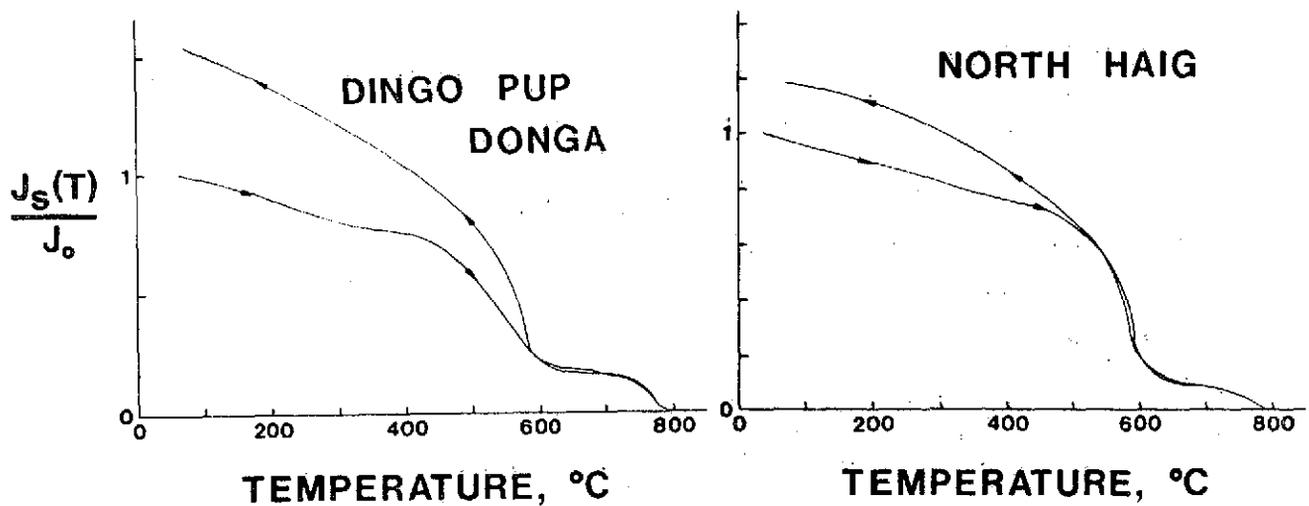


Fig. 3. Saturation magnetization vs. temperature ( $J_s$ -T) curves for the two badly weathered ureilites, Dingo Pup Donga and North Haig. These curves indicate a substantial contribution from both initial magnetite and low-nickel ( $\leq 2\%$ ) metallic-iron. In addition the presence of some substance, probably troilite, which alters into magnetite during the course of the experiment is indicated as evidenced by the increased saturation magnetization observed upon cooling. This is similar to behavior noted in many C2 and C3 chondrites [2,3].

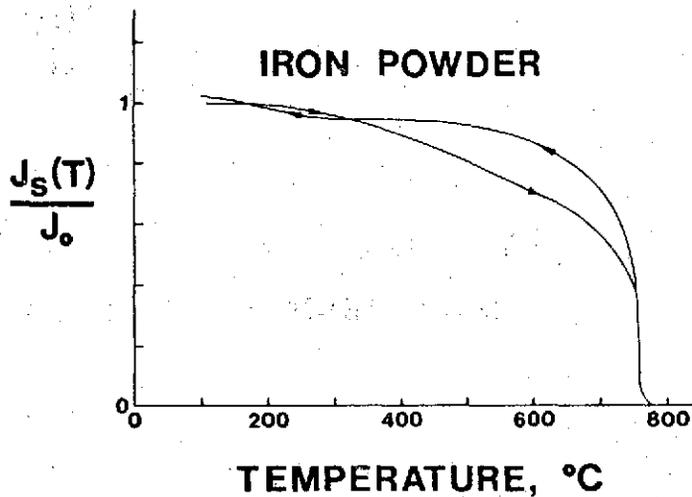
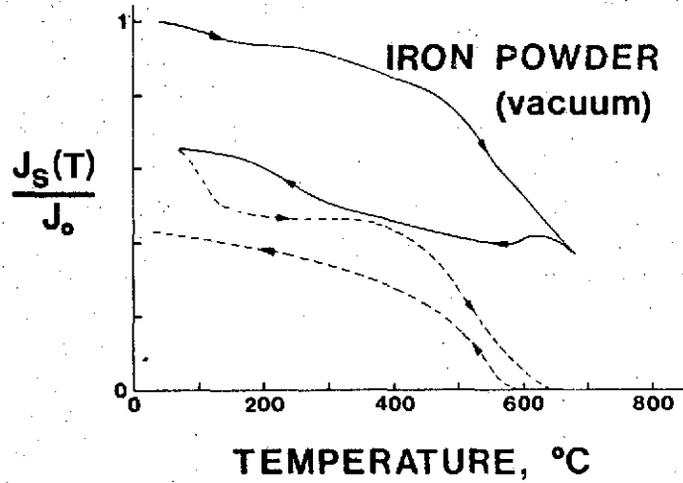


Fig. 4. Saturation magnetization vs. temperature ( $J_S$ -T) curves for iron powder run under vacuum condition compared to that run under controlled oxygen fugacity. It is obvious that superior behavior is found when the oxygen fugacity is controlled.